Fast Risetime Reverse Bias Pulse Failures in SiC PN Junction Diodes

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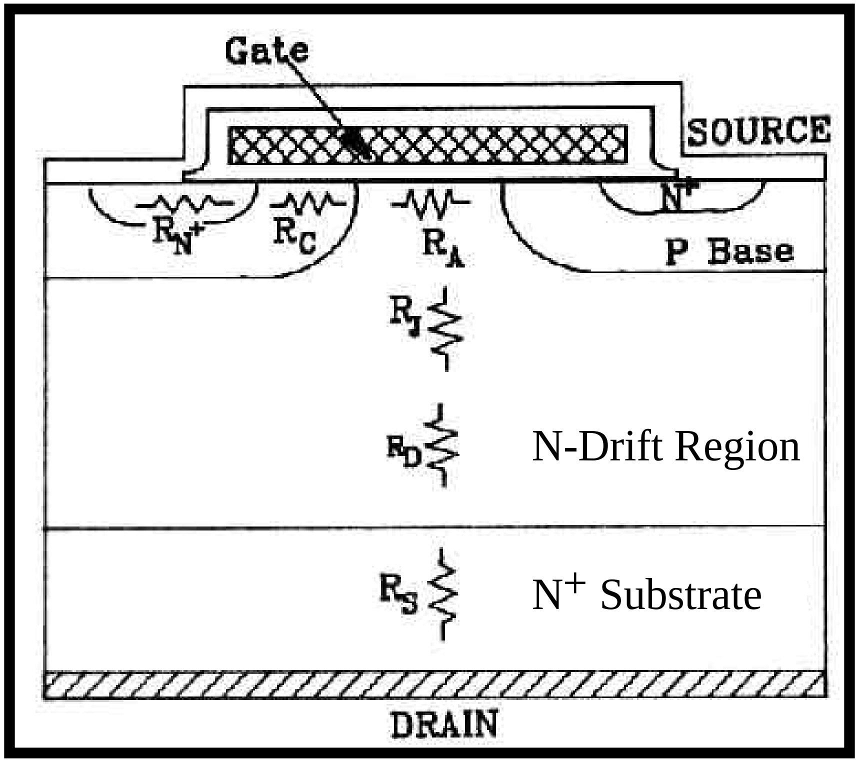
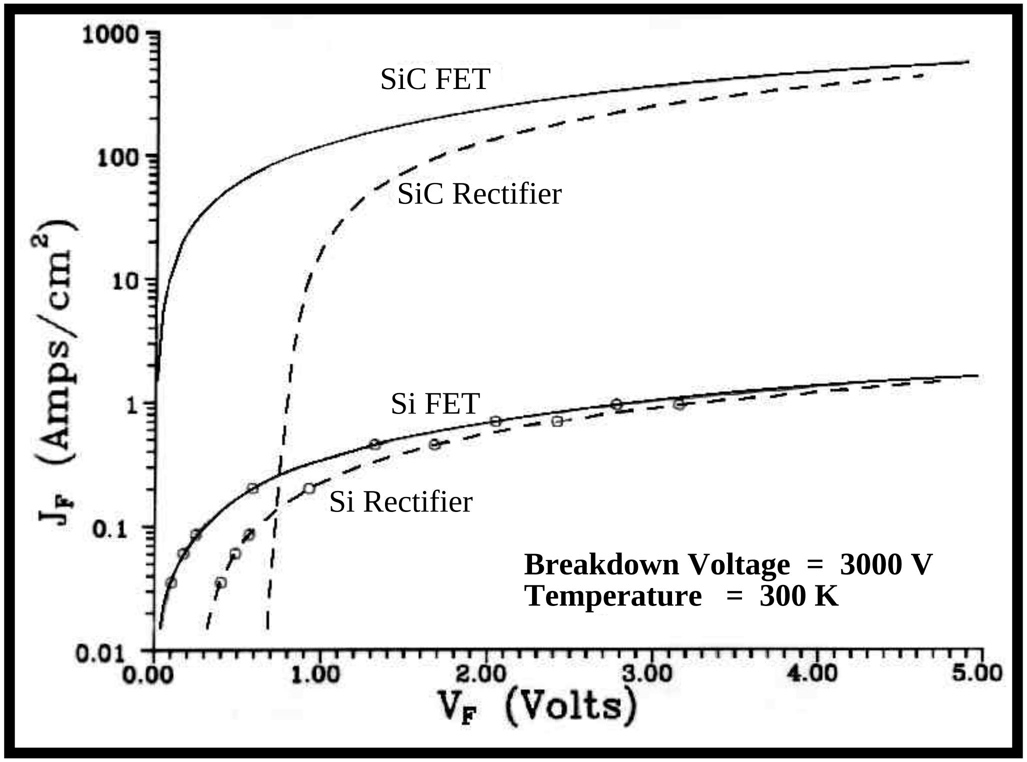
Theoretical SiC Power Device Advantages

High Breakdown Field → Smaller, Higher-Doped Drift Regions
Greatly Reduced ON Resistances

Bhatnagar & Baliga, IEEE Trans. Elect. Dev., Vol 40, No. 3, p. 645, (1993)



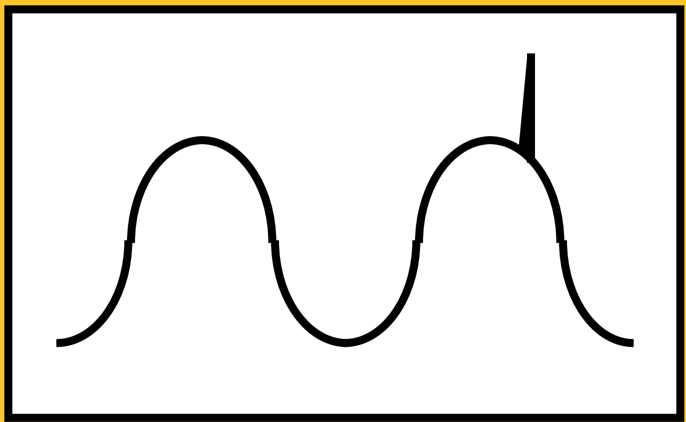


"This would allow almost a twentyfold reduction in the chip size..."

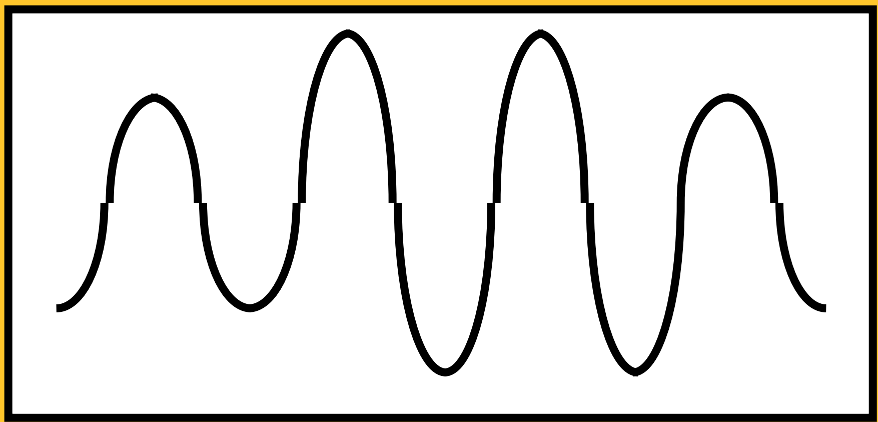
Power Electronics Reliability

Fact: Overvoltage glitches occur in many kinds of power systems.

Impulse



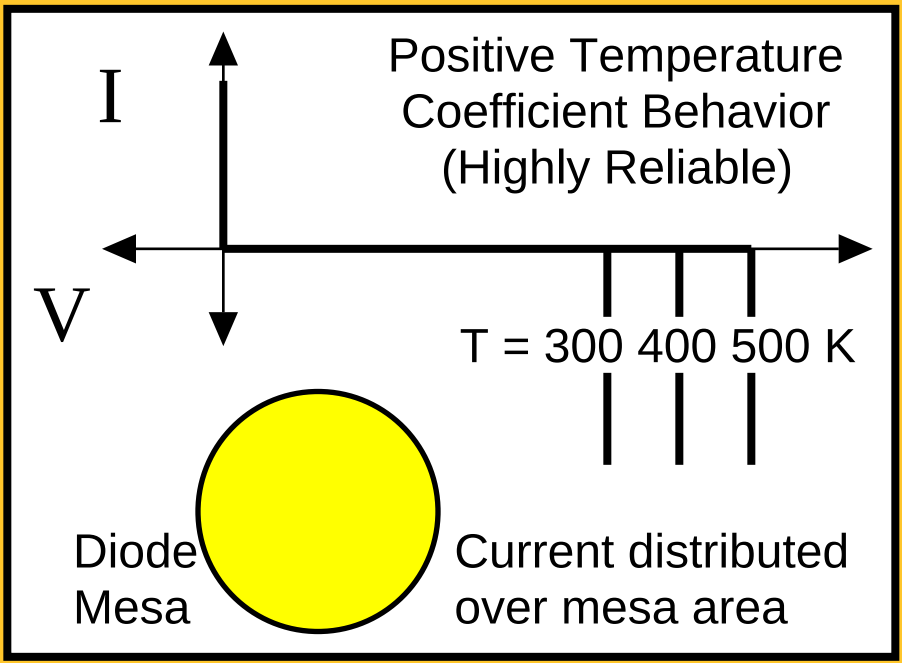
Swell



For many power systems to function highly reliably, components within power system circuits must be able to withstand brief overvoltage events without damage.

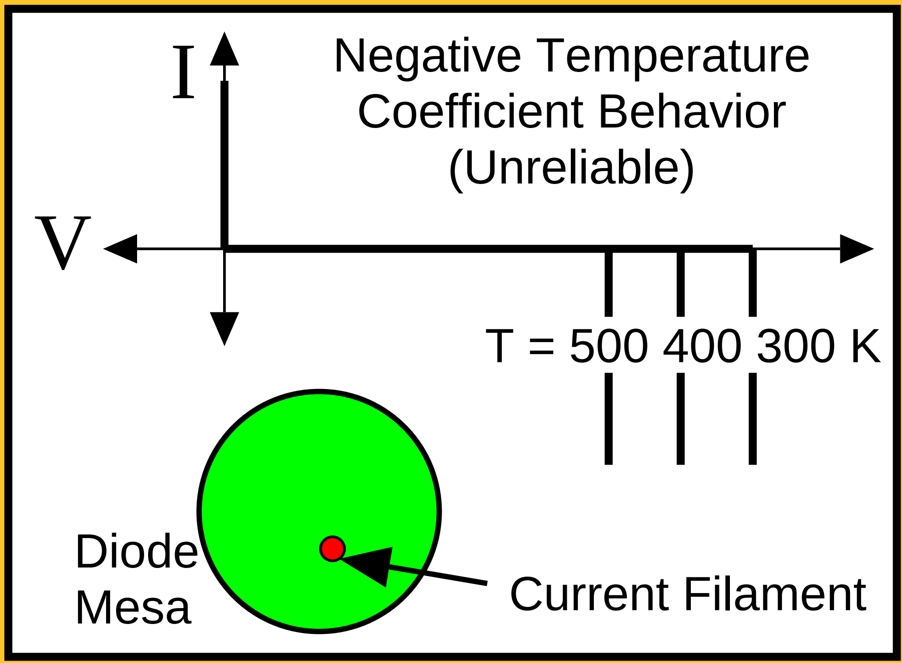
For rectifiers in a high-power circuit to withstand without damage overvoltage glitches that temporarily bias them into reverse breakdown, they must exhibit positive temperature coefficient of breakdown voltage behavior.

Temperature Coefficient of Breakdown Voltage



Breakdown current **decreases** as temperature increases, **reducing** current flow at any junction hotspots.

Breakdown current flow is distributed over entire junction area.



Breakdown current **increases** as temperature increases, **intensifying** current flow and heating at junction hotspots.

Breakdown current flow is focused through localized hotspot forming current filament, hotspot rapidly overheats causing junction damage.

Breakdown Behavior of SiC

Key Question: Can positive temperature coefficient behavior be obtained in SiC?

Previous work on 6H-SiC has indicated negative temperature coefficient behavior.

Not much published on breakdown properties of 4H-SiC junctions.

Potential Factors Impacting Measured SiC Breakdown Properties

A. Material Quality Issues (Solvable with Technology Development)

1) Crystal Defects (Micropipes, Screw Dislocations, Inclusions)

2) Contaminants, Deep Levels

B. Inherent Material Property Issues

1) Band Structure (Bandgap, Carrier Transport Properties)

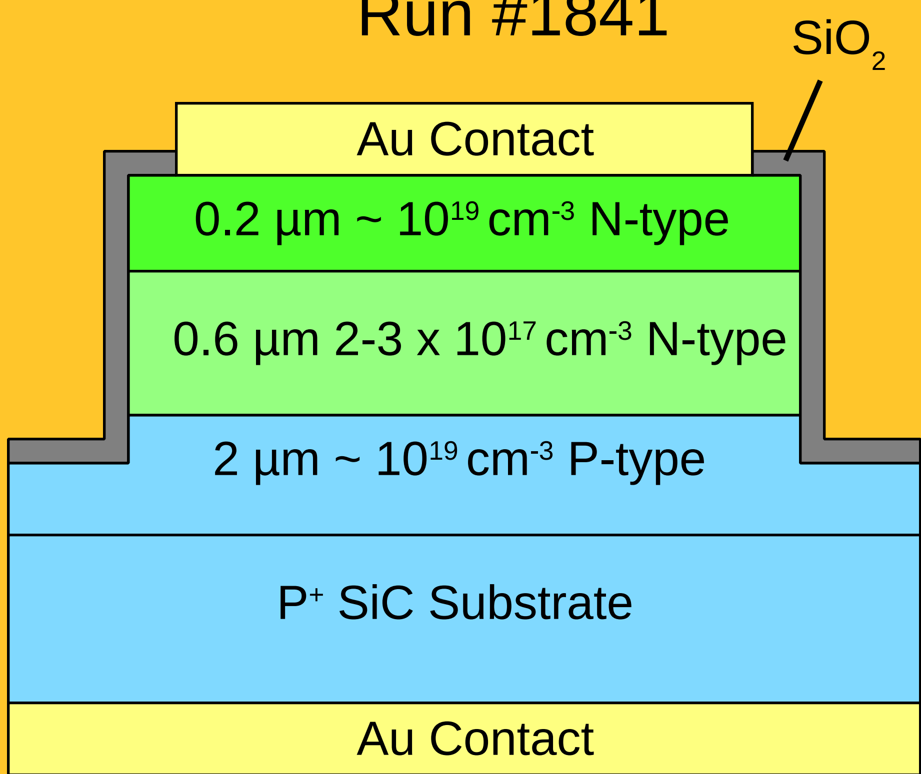
2) Incomplete Ionization of Dopants (Carrier Freeze-out)

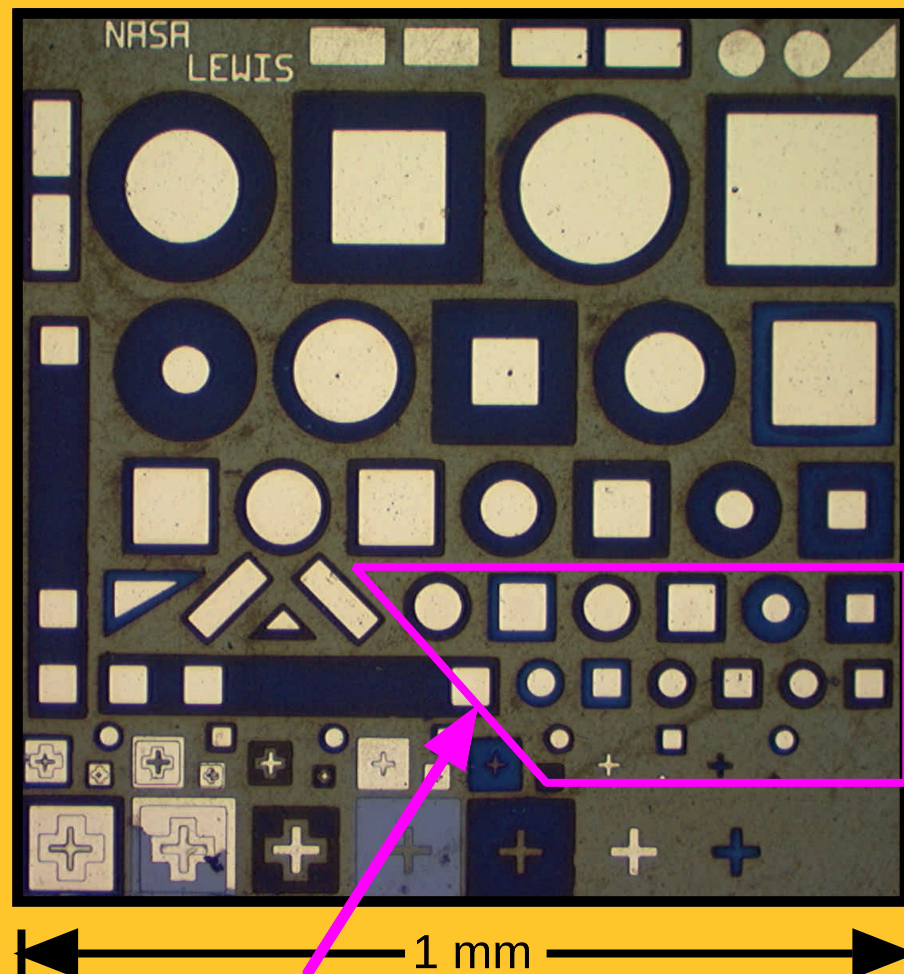
C. Device Geometry

D. Measurement Techniques

6H & 4H SiC P+N Junction Diodes

NASA Lewis CVD Growth Run #1841

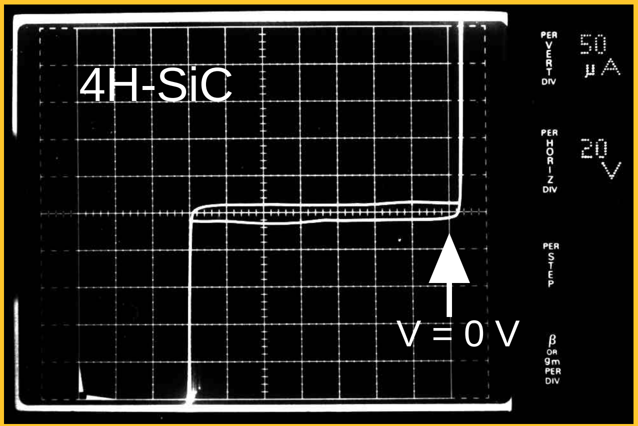


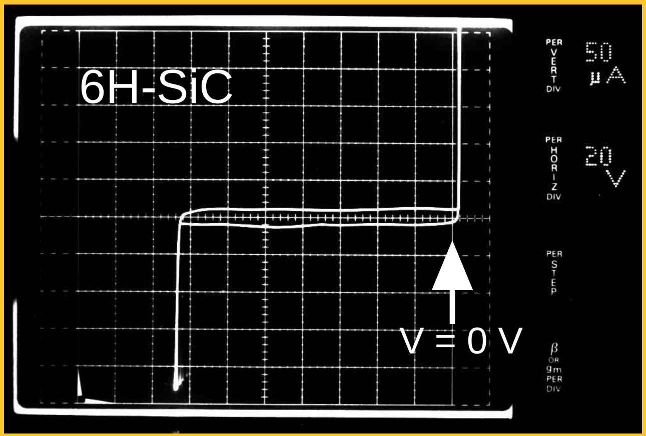


70, 50, & 30 µm Diameter Devices

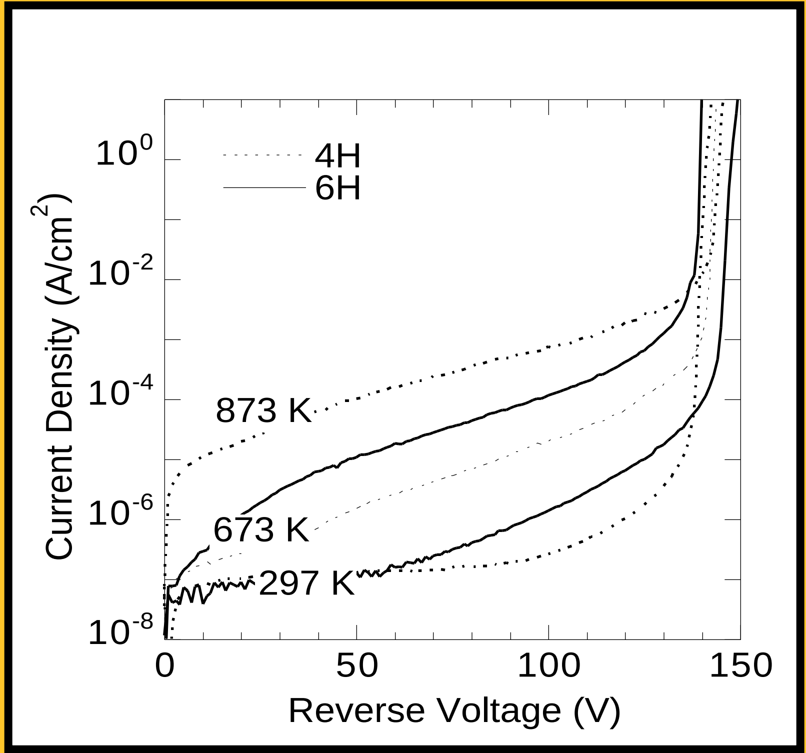
Current-Voltage Measurements

Curve-Tracer Measurements
T_A = 298 K

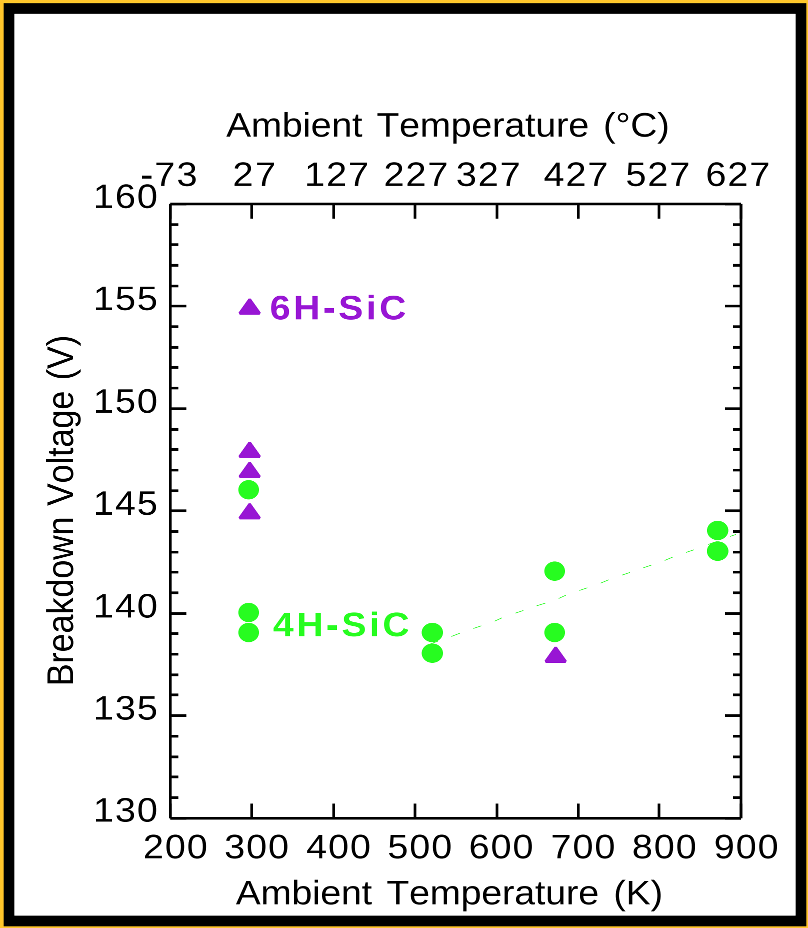




Reverse I-V vs. Ambient Temperature
(Measured by SMU)

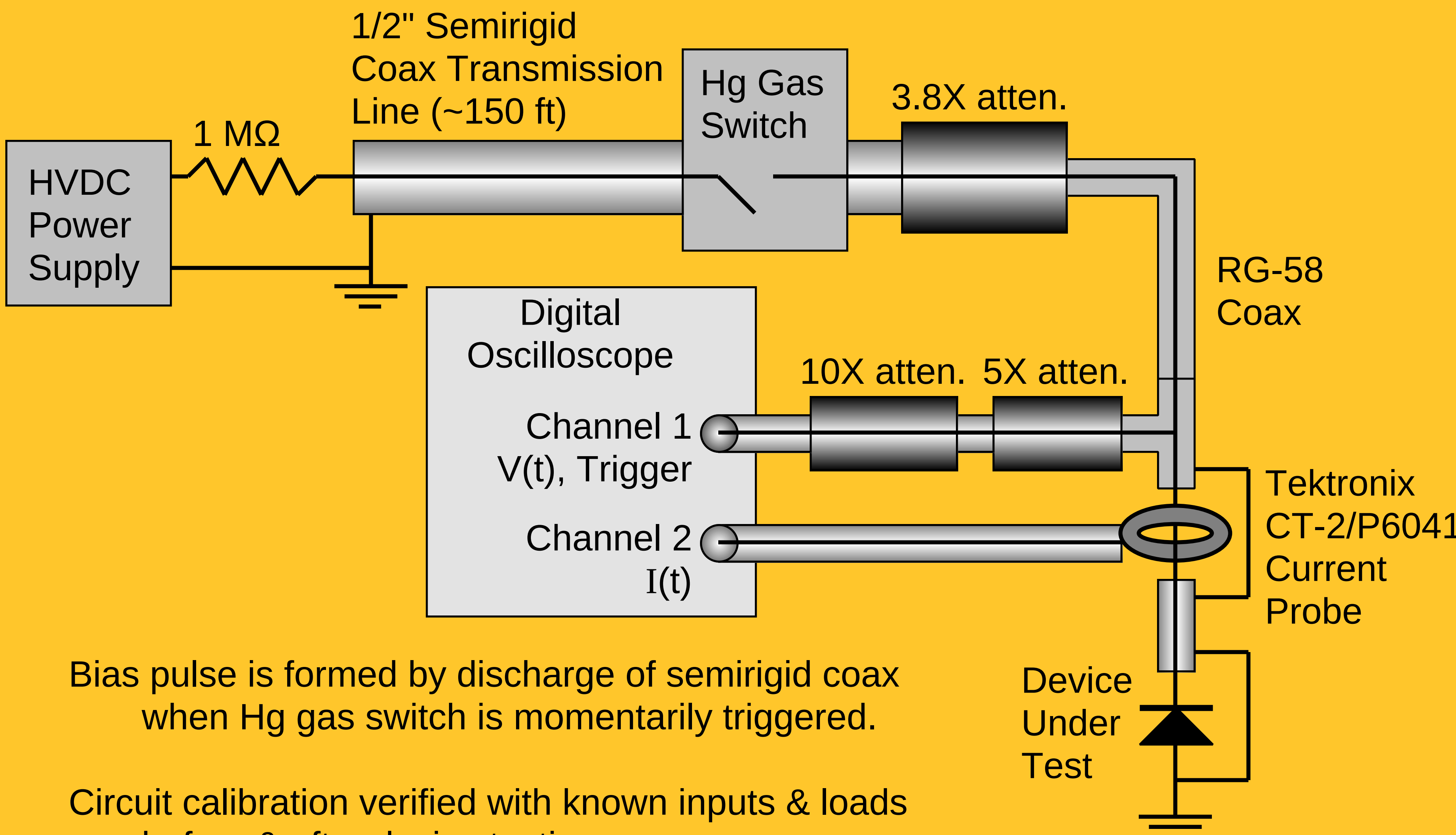


DC Breakdown Voltage vs Ambient Temperature



- 6H-SiC junctions show negative temperature coefficient behavior.
- 4H-SiC junctions show small positive temperature coefficient behavior at higher temperatures.
- Junction heating can cause $T_{Ambient} \neq T_{Junction}$ during conventional curve-tracer I-V measurements.
- Observing time evolution of device current and voltage under breakdown bias pulses is true test of breakdown behavior.

Pulse-Test Circuit



Bias pulse is formed by discharge of semirigid coax when Hg gas switch is momentarily triggered.

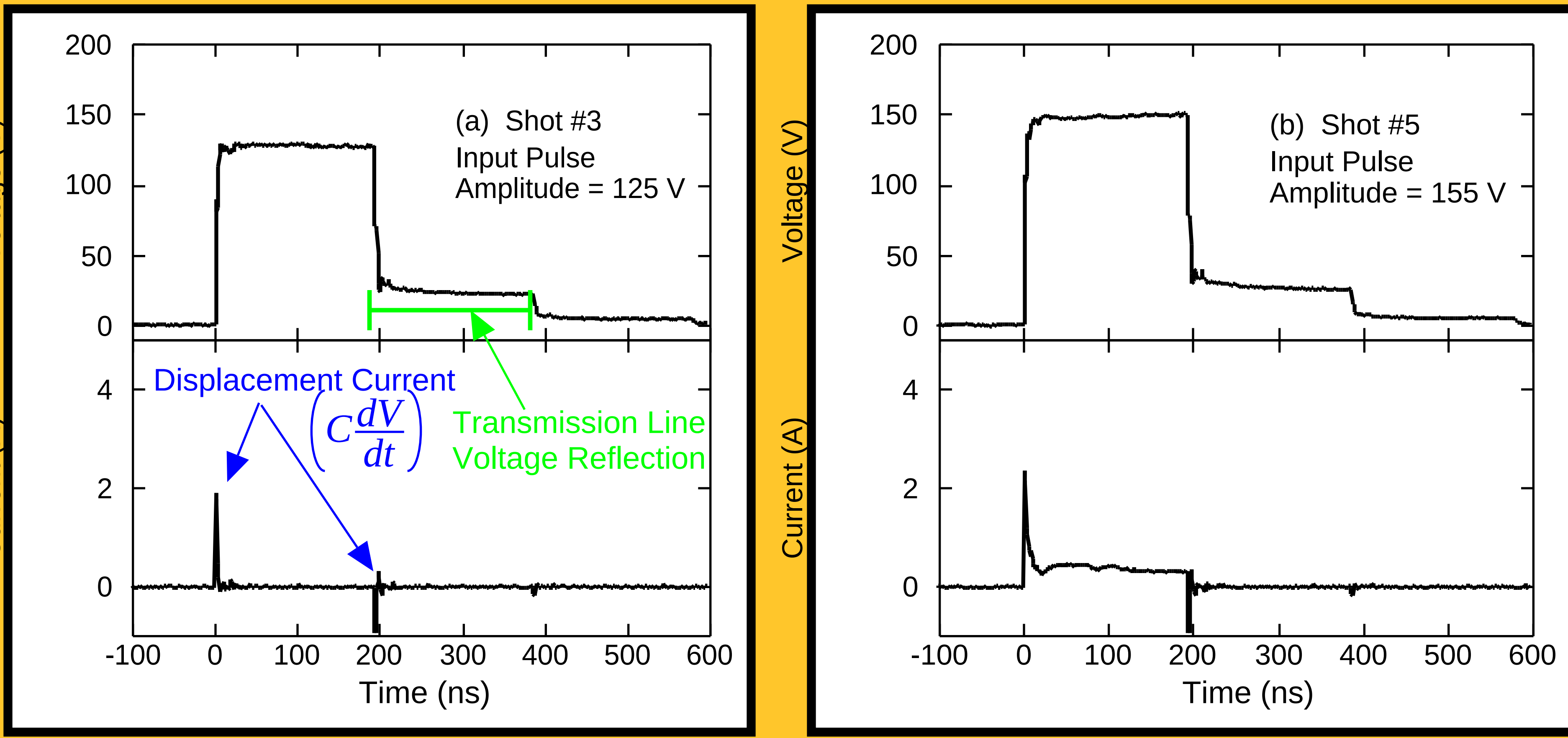
Circuit calibration verified with known inputs & loads before & after device testing.

National Aeronautics and Space Administration
Lewis Research Center

INSTRUMENTATION & CONTROL TECHNOLOGY DIVISION

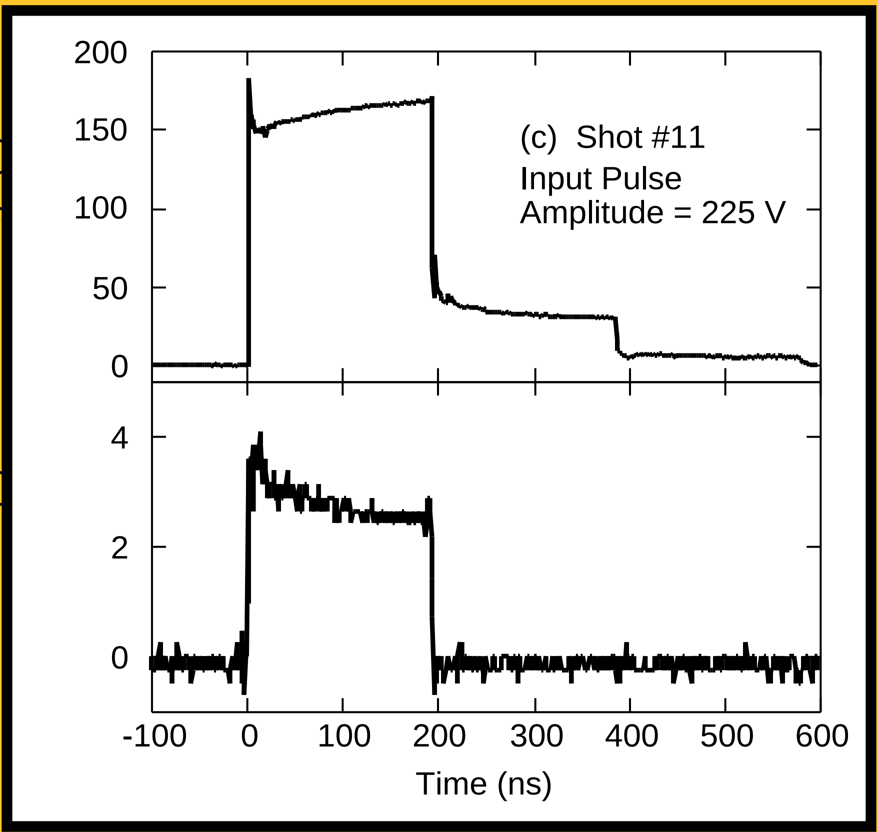
Pulse-Testing of Silicon PN Rectifier

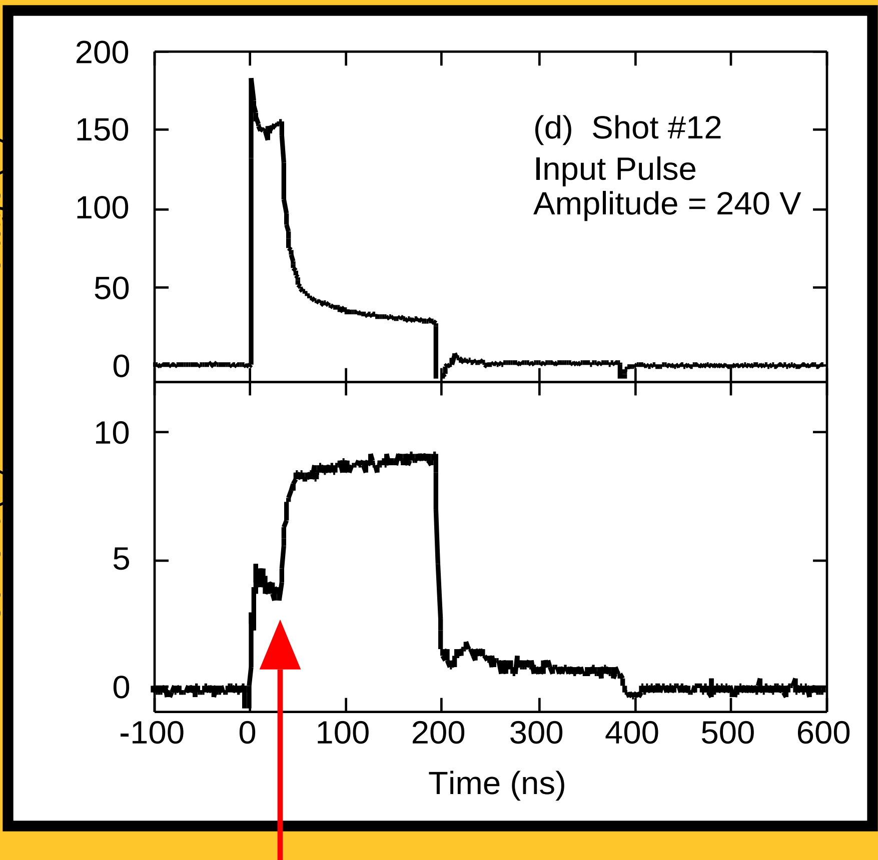
(DC Rating: 150 V, 10 mA)



Pulse-Testing of Silicon PN Rectifier

(DC Rating: 150 V, 10 mA)





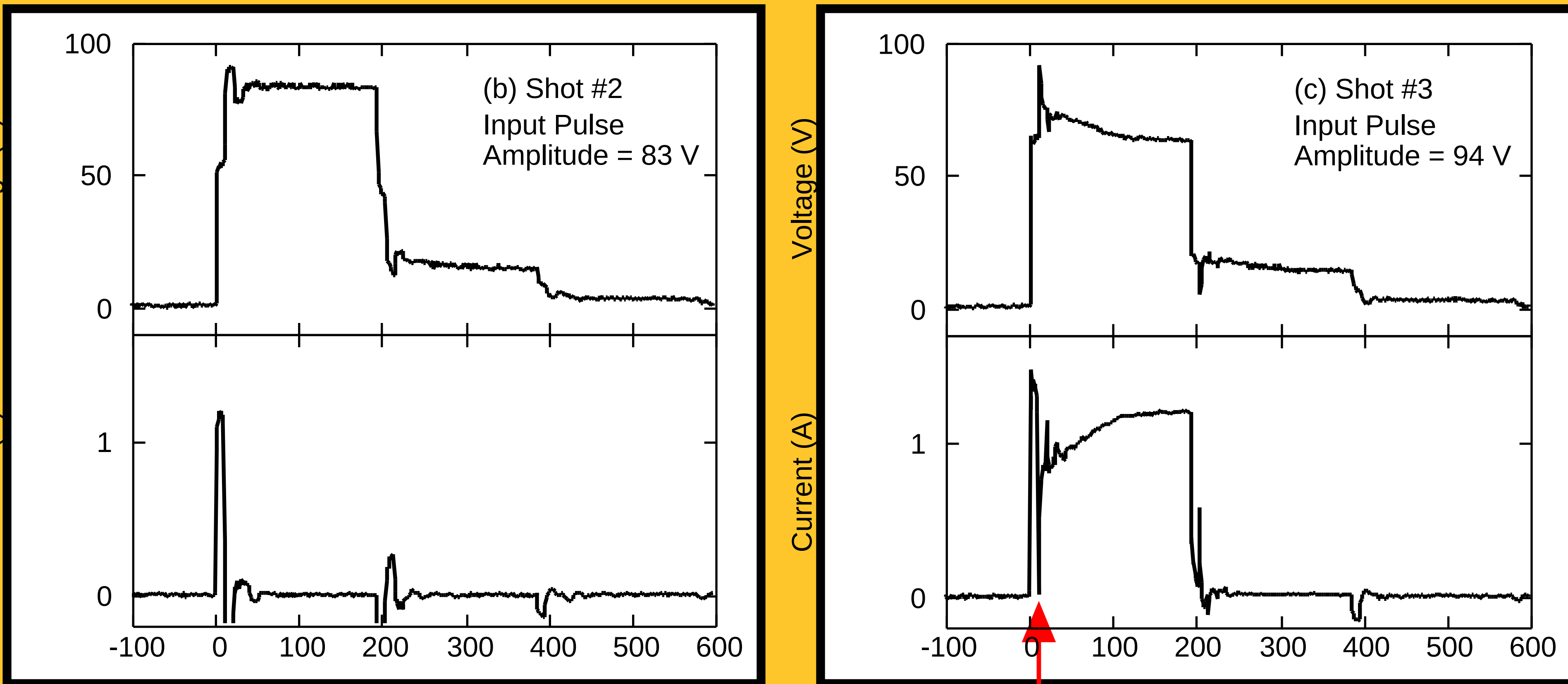
Device voltage rises while current falls as junction self-heats over pulse duration.

Positive temperature coefficient of breakdown voltage behavior.

Device Failure (t = 40 ns)

Short-circuit type failure indicated by voltage collapse coupled with sharp current increase.

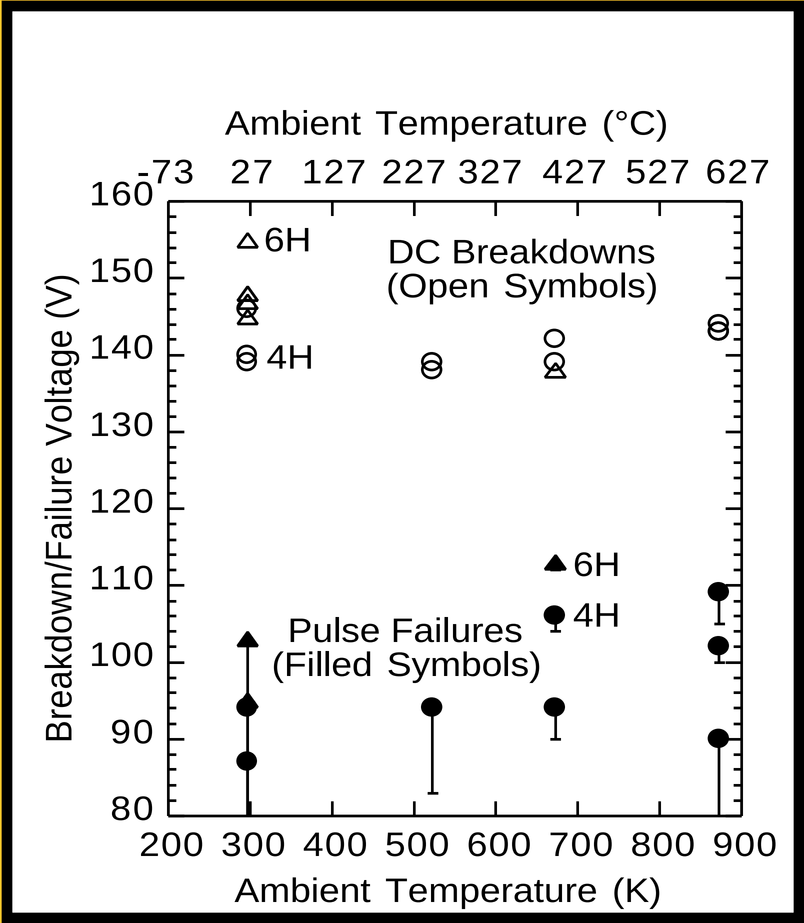
Pulse-Testing of 140 VDC 4H-SiC PN Rectifier



Catastrophic diode failure (t < 20 ns)

Diode fails at pulse amplitude that is less than 70% of curve-tracer ascertained DC breakdown voltage!!!

DC Breakdown & Pulse-Test Failure Voltage vs Temperature



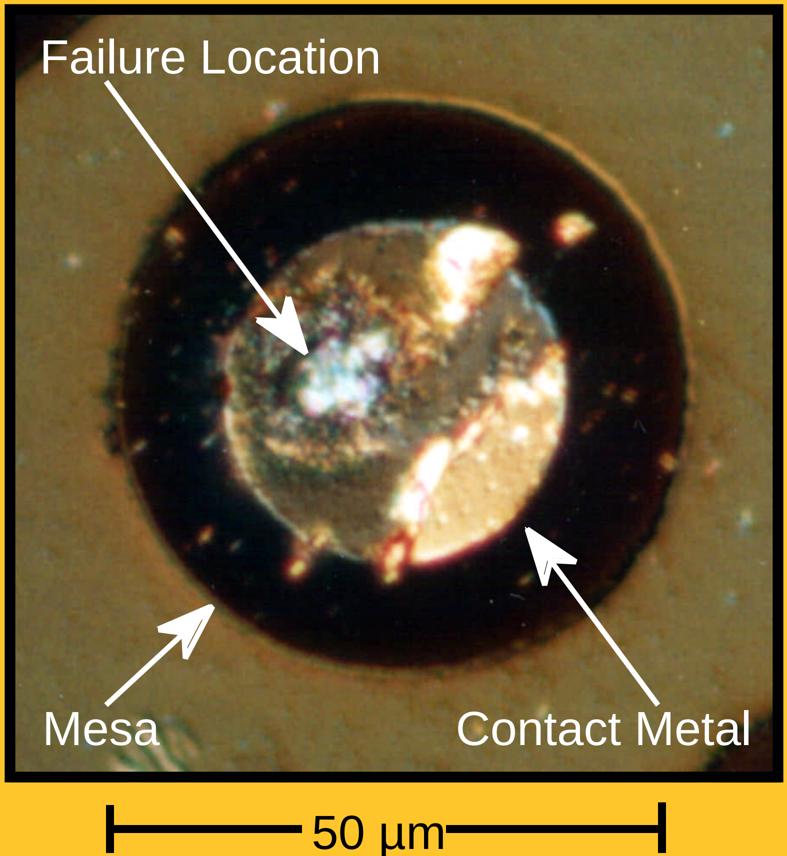
All 4H- and 6H-SiC diodes pulse-tested failed at pulse voltages significantly below the DC-measured breakdown voltage.

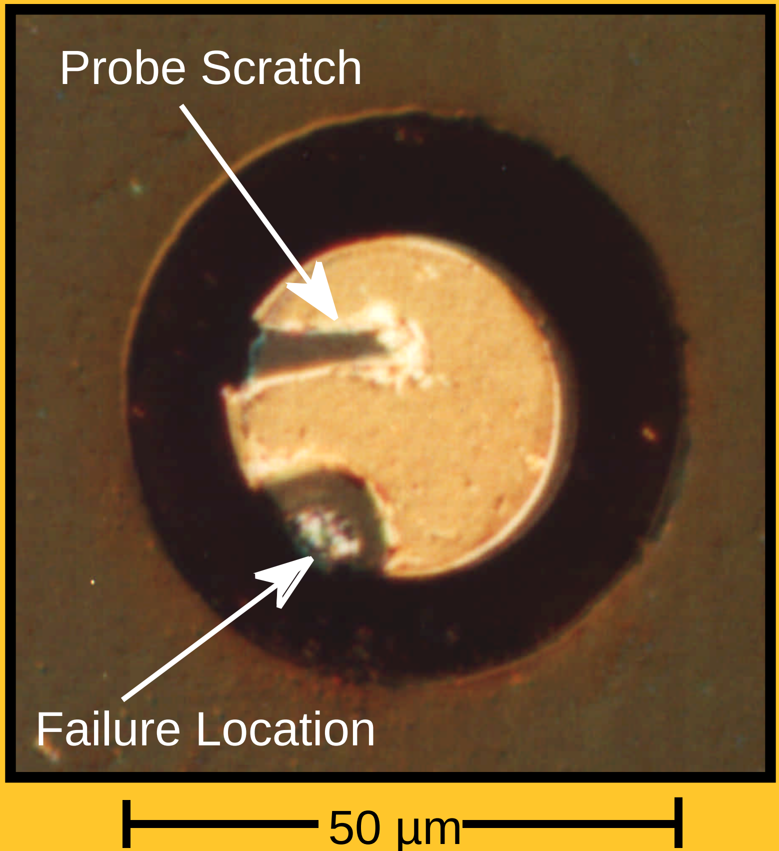
All pulse failures occurred at rising edge of bias pulse (t_{FAIL} < 10 ns).

Following pulse failures, all diodes went from rectifying to resistive shorts.

Post-Failure Microscopic Inspection

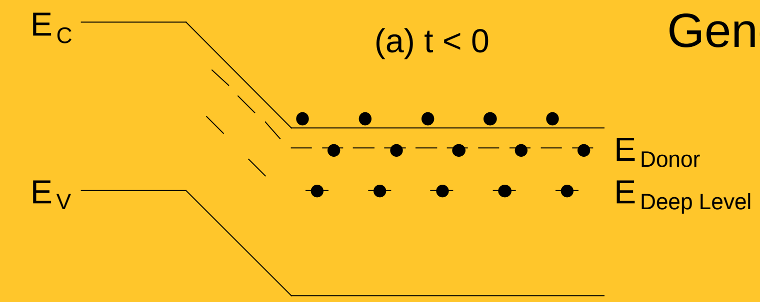
Physical damage occurs within bulk mesa region, consistent with current filament.





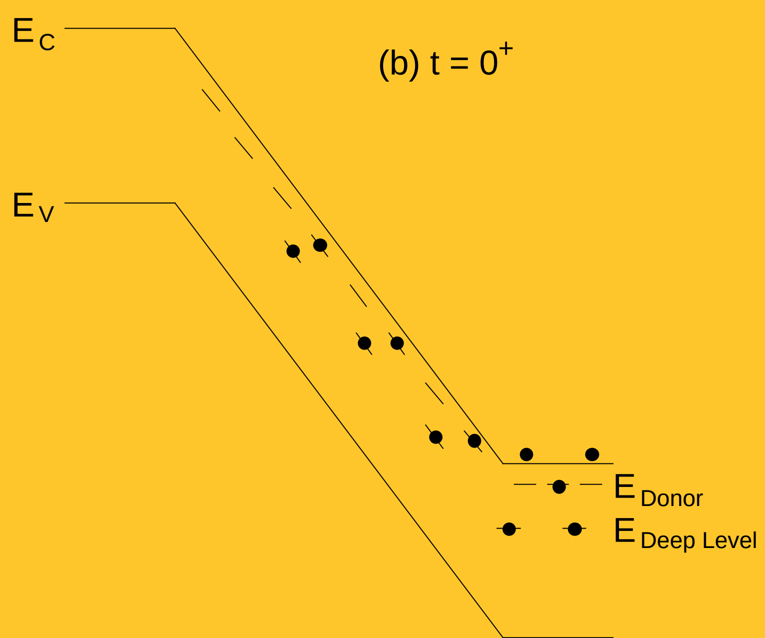
No evidence of edge-related failure was observed.

Proposed Mechanism for Pulse-Test Failure



Generic mechanism for n-type side of rectifier with donor-like impurities.

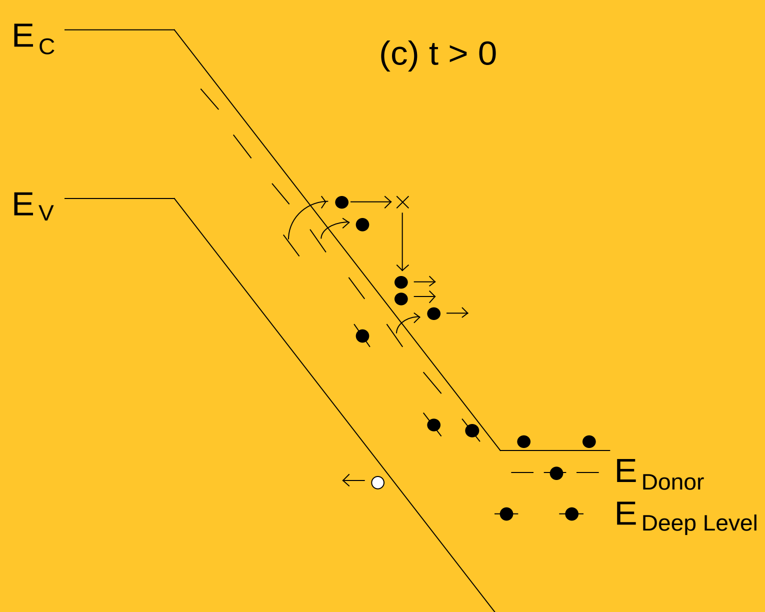
Un-ionized carriers reside in donor & deep level impurity states prior to bias pulse.



Upon application of bias, ionized free carriers respond to applied reverse bias expanding depletion region.

With fast risetime pulse, un-ionized carriers in dopant and deep-level impurity centers do not thermally ionize fast enough to keep up with rising edge of bias pulse.

A significant number of un-ionized carriers remain briefly trapped in dopant and deep-level impurity centers within depletion region.



Dopant and deep-level impurity centers thermally emit carriers into depletion region under high field stress.

Thermal carrier injection into high-field region leads to breakdown instability, current filament.

Thermal carriers   current
heating   hotspot
more thermal carriers
current filament.

Achieving Stable Breakdown in SiC

(in devices without micropipes & dislocations)

Proposed Solution: Eliminate carrier emission from un-ionized impurities.

A. Emission from deep-level centers:

Reduce deep-level defect densities through improved SiC epitaxial growth.

B. Emission from un-ionized ("frozen-out") dopants (?):

Because silicon is ~100% ionized at temperatures of power device interest, the impact of dopant carrier freezeout on breakdown stability has received little prior consideration.

Possible inherent problem for many wide-bandgap semiconductors.

Choose dopants with minimum ionization energies.

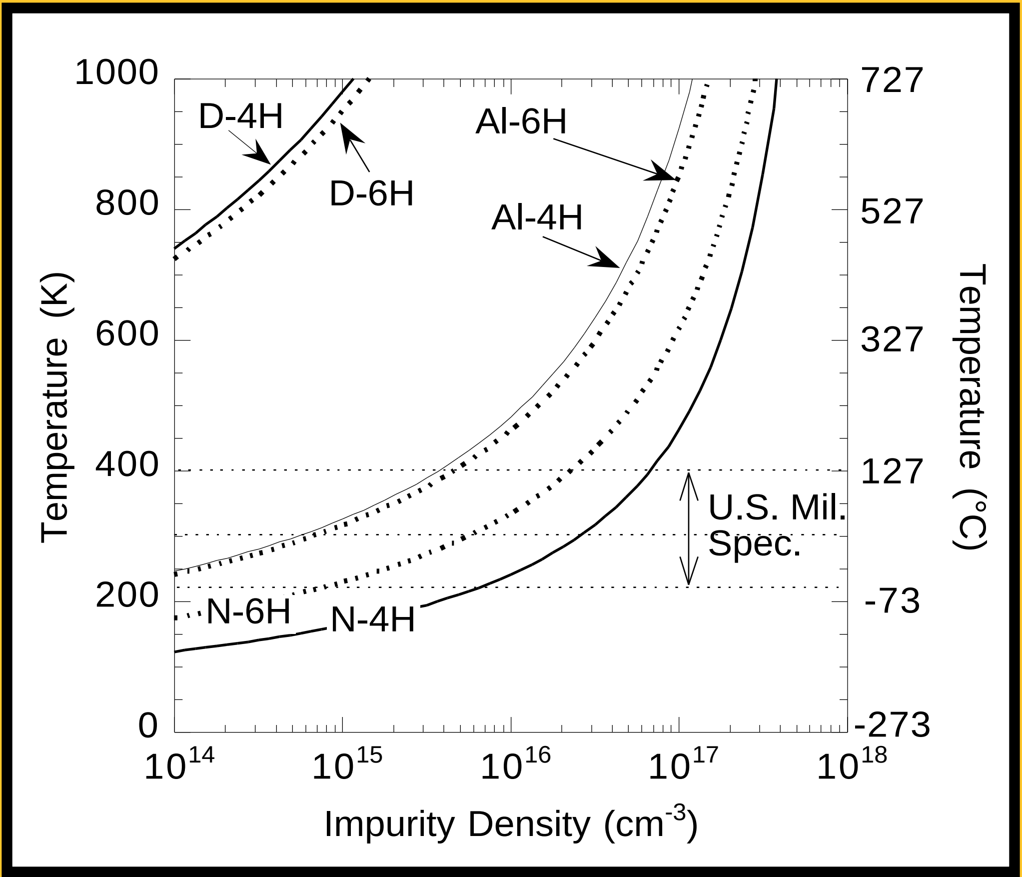
- Deepest energy will govern for multi-energetic dopants.

Use lighter dopings in SiC rectifier junctions.

- % Ionization increases as doping decreases.

What % ionization is necessary for stability? 50%? 90%? 99%? etc.

Theoretical Regions of Breakdown Stability in SiC



First-order theoretical estimate of doping & temperature conditions for which SiC junctions might exhibit unconditionally stable & reliable reverse breakdown properties.

Lines represent where deepest level of each particular dopant is 90% ionized.

For particular device dopant, region above 90% ionized line suggests unconditional breakdown stability.

Summary & Conclusion

- Stable reverse breakdown properties necessary for highly reliable power devices.

  Positive temperature coefficient of breakdown voltage (exhibited in silicon power devices) is an important requirement for high reliability.

- 4H- and 6H-SiC p^+n junction rectifiers tested in this work were amazingly **unreliable**.

  While they showed sharp ~140 V breakdown knees when DC tested, the devices failed when subjected to a single ~100 V fast-risetime pulse.

- Carrier emission from un-ionized deep levels and/or dopants hypothesized as source of SiC breakdown instability.

- Optimization of device design and crystal growth will* lead to SiC rectifiers with reliably stable reverse breakdown properties.

*Late news paper submitted to IEEE Device Research Conference, June 24-26, Santa Barbara CA.

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